2005

Perception of Kanizsa subjective contour requires attention.

Xingshan Li
University of Massachusetts Amherst

PERCEPTION OF KANIZSA SUBJECTIVE CONTOUR REQUIRES ATTENTION

A Thesis Presented

by

XINGSHAN LI

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

September 2005

Psychology

PERCEPTION OF KANIZSA SUBJECTIVE CONTOUR REQUIRES ATTENTION

A Thesis Presented

by

XINGSHAN LI

Approved as to style and content by:

Kyle Cave, Chair

Keith Rayner, Member

Neil E. Berthier, Member

Melinda Novak, Department Head
Department of Psychology

ACKNOWLEDGMENTS

I would like to thank my advisor, Kyle Cave, for his many years of thoughtful, patient guidance and support. And thanks him for his help on my English and helps in my life. His encouragement is really important for me in the last few years. I would also like to thank Keith Rayner, for giving me opportunity to take part in his research projects and giving me financial support. By attending those projects, I learned a lot of things on doing research. These experiences is invaluable and will forever be appreciated. I would also like to extend my gratitude to the members of my committee, Neil K. Berthier, for his helpful comments and suggestions on this project.

Thanks my wife Meihua Ji and daughter Simin for giving me pleasure and support to my life and study.

Thanks all of the members of visual cognition and attention lab for friendship and disussions.

I wish to express to express my appreciation to all the individuals who volunteered their participation in this project.

ABSTRACT

PERCEPTION OF KANIZSA SUBJECTIVE CONTOUR REQUIRES ATTENTION

SEPTEMBER 2005

XINGSHAN LI, B.S., UNIVERSITY OF ELECTRONIC SCIENCE AND TECHOLOGY OF CHINA

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Kyle Cave

We used visual search to explore whether attention is required to perceive Kanizsa-type subjective contour. Unlike previous experiments, we compared search performance with subjective contours against performance with real contours. In the subjective contour condition, both target and distracters were created with subjective contours, and the task was to detect a target defined by orientation or shape. Results showed that visual search was fairly efficient among shapes defined by real contours, but was much less efficient among shapes defined by subjective contours. We conclude that perception of Kanizsa-type subjective contours cannot be performed in parallel and requires attention.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Background

Subjective contour is an illusion in which observers perceive lines, borders, hues, textures and surfaces that are not there (see Meyer & Petry , 1987; Meyer & Fish, 1987). The visual mechanisms that produce subjective contours probably have an important role in the perception of degraded contours in real-world images, and thus comprehending how illusory contours are created will be crucial to our understanding for normal vision. Study of subjective contours and figures defined by them may allow a privileged view of the mechanisms involved in the perception of contours, brightness, shapes, and surfaces (e.g., Grossberg & Mingolla, 1985; Meyer & Petry, 1987). It may also provide a way to understand how the visual system binds together different pieces into a single object (Fahle & Koch, 1995). Subjective contours may be induced by aligned pacmen (Figure 1, A), by offset gratings (Figure 1, B), or by line ends (Figure 1, C). Subjective figure defined by aligned pacmen were first introduced by Kanizsa (Kanizsa, 1979), and this type of figure will be the subjects of the initial experiments presented here.

There is a large body of evidence to support the idea that low-level factors affect subjective figure perception. (Shapley & Gordon, 1985). There is also much evidence that supports the idea that high-level factors affect subjective perception. Some evidence shows that both low-level and high-level processes play important roles in subjective perception. (See Lesher, 1995 for a review.)

Based on this evidence, Davis and Driver (1998) argue that: “it is no longer useful to oppose low-level and high-level accounts in a strictly dichotomous fashion. Instead, what is needed is a more thorough understanding of how the various levels of

processing interact to modulate the percept. " They suggest that "a more specific contrast between distinct levels----namely, that between preattentive and attentive vision may provide a useful fresh perspective."

By definition, 'preattentive' processing occurs before an object is attended. Preattentive processing may represent a fast but relatively high-level abstraction of the visual scene. 'Attentive' processing, of course involves attention, in that at any one time it is selectively applied to a portion of the perceptual input. Information will be processed in detail only with the involvement of attention. One account of the boundary between preattentive and attentive vision is provided by Treisman's (1980) Feature Integration Theory (FIT). Many attention models have been proposed since then, and some dispute the validity of the distinction between preattentive and attentive processes, but this idea is still fundamental to many current theories of attention.

The aim of this paper is to explore whether perception of a Kanizsa-type subjective figure requires attention or not. We will briefly review related recent work, and then will describe a series of experiments that test the preattentive perception of subjective contour.

Are Kanizsa Subjective Figures Detected Preattentively?

Figure 1A shows an example of a Kanizsa-type subjective contour stimulus. Many studies have been done to explore whether attention is required to perceive Kanizsa-type subjective figures. They are briefly divided into two groups. The first group uses the visual search paradigm (Treisman & Gelade, 1980). If the perception is preattentive, then the reaction time for searching for a target defined by subjective contours should not vary much with the number of distracters. However, if perception of an object defined by subjective contour requires attention, the reaction time will

increase with the number of distracters. The second type of evidence comes from neuroscience. Most of these studies use single cell recording, and argue that subjective figure perception may occur at an early stage of visual perception.

Evidence from Visual Search

One of the studies measuring visual search for subjective contours was done by Grabowecky and Treisman (1989). In their experiment (Figure 2 A), the target was a subjective triangle induced by three inducers, or "pacmen". The distracters were sets of pacmen that were misaligned so that they did not induce a subjective figure. Participants were instructed to respond as quickly as possible. The results showed a large effect of set size, which was interpreted to show that subjective figure perception requires attention.

Gurensey Humphrey and Kapitan (1992) and Davis & Driver (1994) questioned Grabowecky and Treisman's (1989) conclusions because of the sudden onset of their stimuli. Rock and Anson (1979) showed that the perception of Kanizsa subjective figures requires a figure-ground reversal, such that the inducing pacmen become the background for the subjective figure. Therefore, Grabowecky and Treisman's (1989) slow detection of subjective contour may be caused by interference from the sudden onset that forces the inducers to be perceived as foreground rather than background.

Davis and Driver (1994) designed an experiment to control the sudden onset effect (Figure 2 B). To avoid a sudden onset of stimuli, a place-holder display, which consisted of black circles in the exact place of each of the pacmen, was presented for 900 ms before the onset of each search display. Also, in their displays the pacmen were organized into clusters. The pacmen in the target cluster faced inward to induce a subjective rectangle figure. The pacmen in each of the distracter faced outward, so

that they did not induce a subjective figure. All the clusters were located along a circle whose center was the location of fixation. With these changes, Davis and Driver found nearly flat slopes of reaction time as a function of set size (about 10 ms/cluster). From these results, they concluded that subjective contour perception is preattentive.

Gurnsey et al. (1996) argued that there are many things that distinguish the targets and distracters in Davis and Driver's (1994) experiment besides the presence of subjective contours. For example, the target and distracters differ in gross outline, and closure. They designed experiments that showed that when subjective contours were eliminated, the visual search was still parallel, and when subjective contours were presented in some conditions, there was serial search. They concluded that subjective contours played no role in the parallel search in Davis and Driver's (1994) result. According to Gurnsey et. al., "there is no evidence that Kanizsa-type subjective contours can be detected in parallel".

Davis and Driver (1998) also noticed the potential shortcomings in Davis and Driver's (1994) experiment. They argued that parallel search may have resulted from strong grouping between the four pacmen in a target cluster. Abundant evidence already exists to show that visual search is easier when target elements group strongly together, to allow segmentation from nontarget elements (Duncan & Humphreys, 1989). The vertical and horizontal edges of the target inducers may simply have been more "free" to group with aligned edges than with the equivalent edges of distracters. To overcome these shortcomings, Davis and Driver (1998) designed a series of experiments (Figure 3). Their displays consisted of sets of clusters of four black pacmen each, with the pacmen arranged so as to generate a Kanizsa subjective square between them. In some of the clusters, one of the black pacmen at one corner of the square was replaced by either a large brown circle or a notched brown circle with a

90° segment taken out of it. Stereoscopic displays were used so that different components of the stimulus array would appear in different depth planes. The participants' task was to search for a large brown notched circle among large brown complete circles. Their result showed that visual search is inefficient if the notched object and distracters were behind an abutting subjective-square surface, but efficient if the notched object and distracters were in front of the subjective-square surface. They explained the result by assuming that when the notched target appeared to lie behind an abutting subjective-square surface, the incomplete target circle would become amodally completed and thus difficult to distinguish from the complete brown nontarget circles within parallel vision. Thus, it is inefficient to search for an amodally completed circle among complete circles.

There are a number of potential problems with Davis and Driver's (1998) experiment. First, four pacmen are required to induce a subjective-square surface. In this series of experiments there are only three of them in one depth level, the notched circle is required to be the fourth pacman to induce the subjective square, but the notched circle or complete circle lies in another depth level. Can a subjective figure be induced efficiently by pacmen located in different depth levels? Second, the black pacmen also present on the search array were not counted as distracters when calculating reaction time slopes. Third, their experiment is based on the assumption that subjective figures may act as an occluding surface. However this assumption is not well established. All of these reasons raise questions about conclusions drawn from Davis and Driver's (1998) evidence.

Subjective Figures Induced by Offset Gratings

Gurnsey et al. (1992) explored the relation of subjective figure and visual attention using subjective figures induced by offset-gratings (Figure 1 B). They found

efficient search for vertical subjective bars among horizontal subjective bars, and efficient search for subjective crescents among subjective oblique bars. Although they found inefficient search for subjective oblique bars among subjective crescents, they concluded that subjective contours defined by offset gratings can be detected in parallel.

However, Davis and Driver (1998) argued that efficient search in Gurnsey et. al.'s (1992) experiment may be easily accounted for by slanted groups of low-spatial-frequency blobs (Figure 4). They noted that with the Gurnsey et al. (1992) type of display, dotted "blobs" of alternating contrast are experienced with unspeeded viewing, along the border between the offset gratings, unless this border is directly foveated. Thus, blurring in peripheral vision might produce the discontinuities on which search is based, without any subjective figures being involved. To illustrate this possibility, they blurred the Gurnsey et al. stimuli with a Gaussian filter. The blurred figure is shown in Figure 4 B. Blobs of opposing contrast are evident at these low spatial frequencies, along the putatively *subjective* borders where the gratings abut. Search based on these blobs alone could presumably produce the parallel result for vertical borders among horizontal borders and for horizontal borders among vertical ones. Thus the preattentive detection of subjective figures in Gurnsey et al.'s (1992) experiment may be due simply to signals in the low spatial frequencies, rather than a reconstruction of the subjective contour.

Many neuroscience studies have shown that the mechanisms underlying offset-grating subjective stimuli differ qualitatively from those responsible for Kanizsa-type subjective figures (Grosof et al., 1993), so one experimental result produced with one kind of subjective contour can not necessarily be generalized to the other. Even if we accept Gurnsey's (1992) conclusion of preattentive detection of offset-grating

subjective contour, we can not conclude that the detection of Kanizsa-type subjective contour is preattentive.

Given the equivocal nature of the experimental results of visual search, the problem of whether subjective contour perception is preattentive is still not resolved. As Gurnsey et al. (1996) argued, "If one wants to argue that Kanizsa-type subjective contours are detected in parallel in a visual search task, one needs to show that parallel detection obtains when the presence of contours is manipulated independently of other properties that might distinguish targets and distracters."

Neuroscience evidence of early subjective contour perception

According to Grosof, Shapley & Hawken (1993), subjective contours defined by offset gratings elicit responses from macaque neurons in V1, which is the first stage of cortical visual processing. However, when single-cell recordings have been performed with Kanizsa figures, responses to subjective contours have not been found in primate V1, arising instead in V2. (von der Heydt, Peterhans, & Baumgarter, 1984) These V2 responses occur even when the monkey's attention is engaged in a visual task at a different location. They interpreted this result as showing that Kanizsa contours can be coded without focal attention in primates. However, these studies using single cell recording technology did not fully control whether attention is involved in the activity of the cell. When recording the activity of a given neuron, they had no direct measure of where their monkeys were attending, and whether there was attention to the neuron's receptive field. Furthermore, even if the presence of a Kanizsa subjective contour is represented in V2, there is no indication whether this information is available to higher-level cognition without attention, or whether it can be used to guide visual search. From these results, we can not conclude that subjective contour perception is preattentive.

Another problem underlying the paradigm is that these findings assume that 'preattentive" processing is equivalent to 'early vision', and that it is done in primary or, perhaps, extrastriate visual cortex. Wolfe (2003) argued that the preattentive stage's representation does not seem to be the same as that formed in early vision. The preattentive stage uses more information than early vision can process, and preattentive processes seem unable to use the full capabilities of early visual processing. Preattentive processes seem to have properties associated with later stages of visual cortical processing (Laack & Olzak, 2002). Wolfe (2003) makes similar observations, and raises more doubts about the link between early vision and preattentive processing by noting that attentive processing seems to have access to the information held by cells in early visual cortex. When taken together, these points seem to require that information be flowing back and forth between lower and higher levels of the visual system. Thus, early processing of subjective contour does not necessarily mean that it is preattentive processing .

Using a change detection technique, Mattingley, Davis and Driver (1997) found that parietal extinction patients may detect changes in either visual field if the pacmen form a subjective surface. From this result, they concluded that the visual filling-in that yields illusory Kanizsa figures is preattentive. Vuilleumier, Valenza and Landis's (2001) study on unilateral spatial neglect patients provided additional evidence to support the idea that subjective contours are detected preattentively. One of their experiments used a bisection task, in which patients were not explicitly required to attend to lateral elements, but judged the midpoint of Kanizsa illusory stimuli, as well as other physically connected or unconnected stimuli of the same length. In some patients, bisection judgements were consistently similar for Kanizsa stimuli with illusory contours and connected stimuli with real contours, but different for

unconnected gap figures, regardless of their length. Participants without neglect did not show this effect. With these findings, they concluded that "grouping by illusory contours can occur preattentively and influence bisection independently from the ability to detect contralateral inducers explicitly, severity of inattention, and other forms of unconscious processing."

Though all of these results point to the conclusion that subjective figure perception is preattentive, all of these experiments use only a single subjective figure in each stimulus display. In these cases, attention seems have no choice but to select this single subjective figure. Thus, it is hard to extend these results to conclude that filling-in of multiple subjective figures in the same display is done preattentively and in parallel.

With the evidence reviewed above, we can not reach a conclusion about whether visual attention is required when perceiving subjective contour. We designed a series of experiments to explore this problem.

Experimental Paradigm

A visual search paradigm was employed in these experiments. In addition to the traditional visual search task we have reviewed above, we included some control trials to exclude the influence of factors other than subjective contour. In these control trials, at the exact location of the subjective contours, we added real lines (Figure 5). Then we compared the search result of these two conditions. The only difference in the experimental procedure between the two conditions was whether the contours were subjective or real. Any difference in search performance must be due to differences in the perception of subjective contours and real contours.

In most visual search experiments with subjective figures, only one subjective figure exists in the stimulus array (Grabowecky & Treisman, 1989; Davis & Driver,

1994). This type of task is a more limited test of the preattentive detection of subjective contours. The stimuli in these experiments never contain more than one subjective figure. Thus, even if such experiments produce results indicating that one subjective figure can be detected efficiently, this would still not show that multiple subjective figures can be coded simultaneously (Davis & Driver, 1998). In this series of experiments, in the subjective contour condition, both target and distracters are all subjective figures.

A number of studies indicate that orientation is a feature that can guide search, and that many shape differences can also guide search (Wolfe, 2004). Therefore, we used oriented rectangles as search items in some experiments, and squares and triangles in others. These figures are assumed to produce efficient search when the stimuli are created with real contours.

In the key part of these experiments, we compare the performance of visual search when the figure is induced only by circular inducing shapes, or *pacmen* (*subjective* condition, Figure 5 A) and when the figure is induced by both pacmen and real contours (*both* condition Figure 5 B). If perception of subjective contour does not require attention, then we may predict that the performance in the *subjective* condition and the *both* condition will not differ substantially. The search slope as the function of set size will be quite flat. Otherwise, if perception of subjective contour requires attention, then we predict that search will be more inefficient in the *subjective* condition than in the *both* condition.

CHAPTER 2

KANIZSA TYPE SUBJECTIVE FIGURE

Experiment 1

A visual search paradigm is employed in these experiments. Some control trials are included to exclude the influence of factors other than subjective contour. In these control trials, real lines appeared at the locations that would otherwise have subjective contours. Search performance was compared across these two conditions. The only difference between the two conditions is whether the contours are subjective or real. Any difference in search performance between these conditions must be due to differences in the perception of subjective contours and real contours.

Apparatus

Stimuli were presented on a 21 inch NEC MultiSync FE990 monitor controlled by a Mac G4. Participants kept their chin on a chin-rest located 57 cm away from the monitor. Participants responded by pressing a button on a Superlab button box.

Participants

All of the participants were recruited from a subject pool of undergraduate students in UMASS who participated for course credit. All subjects had normal or corrected to normal vision. No participant participated in more than one of the following experiments. The average age was 20.3, ranging from 18 to 28. There were 18 participants in Experiment 1.

Stimuli

The task in this experiment was to search for a horizontal rectangle target among vertical rectangle distracters. There were three blocks of trials in Experiment 1. In one block the rectangles were defined by real contours alone. In another block they were

defined by subjective contours created by pacmen. Another block included both real lines and pacmen together, so that the rectangles were defined by both real and subjective contours (Figure 6). These conditions will be labeled as *line*, *subjective*, and *both* conditions respectively. The order of these blocks was carefully balanced to ensure that the same number of subjects were tested in each possible order.

The diameter of each pacman was 16.8 mm, or 0.83° of visual angle. The size of the induced rectangle was 25.2mm by 37.8mm, or 2.55° by 3.73° of visual angle. To prevent the density of pacmen from differing too much for different set sizes, the following method was employed when producing stimuli: The location of the first rectangle was selected randomly. The location of the next rectangle was chosen so that one of its inducing pacmen was no farther than 25.2mm from one of the existing pacmen. This design kept the density of pacmen relatively constant across the different set sizes. The black pacmen was displayed on white background. In the *both* and *line* condition, the real contour was a gray line (cd / m^2).

There were four different set sizes in the search array: 5,7,9,and 13. In half of the trials, a horizontal rectangle was present as the target. Thus there were 2 (target present or not) X 4 (set size) conditions in each block. There were ten trials for each condition, or a total of 80 trials in each block of the experiment. The order of these 80 trials was randomized within each block. Before each block, there were 32 practice trials.

Procedure

At the beginning of each trial, a red cross appeared at the center of the screen for 1 second. Gurnsey et al. (1992) and Davis and Driver (1994) argued that the sudden onset of high-contrast inducing pacmen may have overpowered any signal for the subjective target in Grabowecky and Treisman's (1989) study. Following Davis

and Driver (1994), place holders were presented for 1 second at the positions that would later be occupied by pacmen. Davis and Driver (1994) used black circles as place holders, with one quarter of each circle removed when the time came to induce the subjective figure. Because this sudden offset of the quarter of the black circle might have attracted attention to that part of stimuli, we used place holders with the same shape and same location as the pacmen, but with a random rotation applied to each. After an exposure of 1 sec, the inducers were all simultaneously rotated to the correct orientation to induce the subjective figure. In the *line* condition, the place holders disappeared after 1 second, and the rectangle stimuli appeared drawn with real lines, with no inducers present. In all three conditions, the search array was present until participants responded.

Participants responded by pressing the right button on the button box if a target was present, and the left button if the target was absent. Participants were instructed to respond as quickly and as accurately as possible. Error responses were indicated by a sound.

Results

The overall accuracy was 97.2%. Because the accuracy was very high, it was not analyzed further. Only trials with correct responses were included in the analyses, which excluded 120 trials (2.8%) among 4320 trials. Trials with reaction time shorter than 100 ms or longer than 10000ms were also excluded, which resulted in an additional 7 trials being excluded.

The results are shown in Figure 7. For the *both* condition, the slope of the function relating mean reaction time and set size is 10.6ms/rectangle when the target was present, and 58.2 ms/rectangle when the target was absent. In contrast, in the *subjective* condition, the target-present slope is 52.2 ms/rectangle, and the target-

absent slope is 115.1 ms/rectangle. The ratio for target absent vs. target present is about 2.2. In the *line* condition, the target-present slope is 18.2 ms/rectangle, and the target-absent slope is 43.5 ms/rectangle.

A series of pair-wise t-tests was conducted on the search slope data, derived by linear regressions of the mean RTs against set size for each participant. For target present situations, the slopes are significantly different between the *both* and *subjective* conditions, $t=-4.5$, $p<0.01$; and between the *line* and *subjective* conditions, $t=-4.1$, $p<0.01$. However, the slopes are not significantly different between the *both* and *line* conditions, $t=-1.721$, $p=0.1$. For the target absent condition, all of the pairs of slopes are significantly different, $t=2.75$, -5.9, and -6.5 for *both* and *line*, *both* and *subjective*, *line* and *subjective*, respectively, $ps<0.05$.

Discussion

Although it is very difficult to distinguish between serial and parallel search (Townsend, 1990), some visual search theories are based on the assumption that serial search has the following two properties: (a) The search slope is larger than 10ms/item; (b) The ratio of slopes between target absent and target present conditions is about 2 (Wolfe, 1998). Using this standard, the search in the *subjective* condition apparently falls in the category of serial search. The only difference between the *subjective* condition and the *both* condition is whether real contours were present or not. Regardless of how serial search defined, it is apparent that search in the *both* condition is much more efficient than in the *subjective* condition, reflecting a strong difference between perception of subjective contours and real contours.

Experiment 2

In Experiment 1, both target and distracters were rectangles. In Experiment 2 we used squares and triangles to explore whether we find a similar pattern of search performance when the target is defined by shape rather than orientation.

Stimulis and procedure

In this experiment, the task was to search for a square among triangles. The stimuli were shown in Figure 8. To exclude the possibility that the shape of the pacmen plays some important role in visual search, the shape was modified so that all the pacmen, whether they induced a rectangle or triangle, were identical in shape. Thus each pacmen had two gaps: one was 90° to create the vertex of a rectangle, the other was 60° to create the vertex of an equilateral triangle. All of the other aspects of the experiment were identical to Experiment 1. Another 18 participants were recruited from the same subjects pool.

Results

Onc subject was excluded from analysis because of extremely long reaction times. The mean reaction time for all the participants was 711ms, and the standard deviation was 230. The excluded participant had a mean reaction time of 1430, and the next largest mean reaction time was 974 ms.

The overall accuracy in this experiment was 97.2%. Because the accuracy was very high, it was not analyzed further. Only trials with correct responses were included in the analyses, which excluded 121 trials (2.8%) among 4320 trials. Trials with reaction time shorter than 100 ms or longer than 10000ms were also excluded, which resulted in an additional 10 trials being excluded.

The results are shown in Figure 9. For the *both* condition, the slopc of reaction time function was 6.11 ms/shape when the target was present, and 32.59 ms/shapc

when the target was absent. In contrast, in the *subjective* condition, the target-present slope was 20.80 ms/shape, and the target-absent slope was 53.52 ms/shape. In the *line* condition, the target-present slope was 8.51 ms/shape, and the target-absent slope was 25.03 ms/shape.

A series of pair-wise t-tests was conducted on the search slope data, derived by linear regressions of the RT means against set size for each participant. For target present trials, the slopes are significantly different between the *both* and the *subjective* conditions, $t=-3.83$, $p<0.01$; and between the *line* and the *subjective* condition, $t=-3.98$, $p<0.01$. However, the slopes are not significantly different between the *both* and the *line* conditions, $t=-0.76$, $p=0.46$. For the target absent condition, the pairs of slopes are significantly different between the *both* condition and the *subjective* condition ($t=-2.73$, $p<0.05$), and between the *line* condition and the *subjective* condition ($t=-3.64$, $p<0.05$). However, the slopes are not significantly different between the *both* and the *line* conditions ($t=1.36$, $p=0.19$).

Discussion

Although different stimuli were used, the result of Experiment 2 was the same pattern as Experiment 1. Search is difficult and strongly affected by set size in the *subjective* condition, but is much more efficient in the *both* condition. This result confirmed the conclusion from Experiment 1 that perception of Kanizsa subjective contour requires attention.

In this experiment, all of the slopes are smaller than the corresponding slopes in Experiment 1, reflecting the fact that the search task in experiment 2 is generally easier than that of Experiment 1.

Experiment 3

There is an alterative explanation for these experiments. One may argue that the inefficient search in the *subjective* condition is due to retinal eccentricity. The decrease in spatial resolution in the periphery may have prevented subjects from perceiving the edges of the inducing pacmen when they were at the edges of the display. Search may have been more difficult at the larger set sizes in these experiments merely because there were more stimuli at extreme eccentricities. Experiment 3 is designed to test this possibility.

Participants

8 participants were recruited from the same subject pool of the first 2 experiments.

Stimuli and procedure

Participants were instructed to focus attention at a red cross in the center of the display. After 1000 ms, a single set of four pacmen appeared somewhere in the display for 187 ms. These pacmen may or may not have been aligned to produce a subjective figure, as shown in figure 10. The display time is brief enough to prevent any eye movement. The distance from the red fixation cross to the group of pacmen varied from trial to trial, and was either 6.4°, 9.6°, 12.7° or 15.7° of visual angle. The task of participants was to judge whether a subjective figure was present or not. Participants were told that only accuracy was important. Each participant performed 32 practice trials and 240 experiment trials.

Result

Responses were reasonably accurate at every distance. There was a descrease in accuracy as eccentricity increases, and the accuracy in the worst condition was 78% (see Figure 11). Eccentricity may account for some of the set size effect in the

previous experiments, but even at the longest distance, subjects are able to perceive the pacmen that induce the subjective contours fairly accurately. Eccentricity alone does not seem to be able to account for the large effect of set size in searching among subjective contours. The effect of eccentricity will be more fully controlled in Experiment 4 by limiting the size of the display.

Experiment 4

One of the differences between Experiments 1 and 2 and Davis and Driver's (1994) experiment is the visual angle of search array presented on the screen. To exclude the possibility that the result of the first two experiments is due to influence of retinal eccentricity effect, in Experiment 4, the stimuli spread a visual angle that was comparable with Davis and Driver's (1994). If the result in the first two experiments was due to eccentricity effect, we will expect a more efficient search in the *subjective* condition in this experiment and a less difference between the *subjective* condition and the *both* condition.

Stimulis and procedure

The viewing distance was 112 cm. Stimuli were displayed in a 88.15mm by 88.15mm square at the center of the monitor. This square extended oer a visual angle of 4.5°X4.5°. The pacman was 0.4° in diameter. Because of the limited display area, set sizes of 5, 7 and 9 were used. All of the other aspects of this experiment were exactly the same as Experiment 1. 18 participants from the same participant pool who had not participated in the first three experiments were recruited to participate in this experiment.

Result

The overall accurancy was 95.8%. Because the accuracy was high, it was not analyzed further. Only trials with correct responses were included in the analysis, which excluded 145 trials among 3420 trials. Those trials whose reaction time were shorter than 100 ms or longer than 10000ms were excluded, which excluded another 3 trials. Overall 4.3% trials were excluded.

The results are shown in figure 12. In the "both" condition, the slope of the mean reaction time as a function of set size was 8.23 ms/rectangle when the target was present, and 21.62 ms/rectangle when target was absent. In the *line* condition, the target-present slope was 23.09 ms/rectangle, and target-absent slope was 15.28ms/rectangle (Figure 13). In contrast, in the *subjective* condition, the target-present slope was 65.97 ms/rectangle when target was present, and the target-absent slope was 94.94 ms/rectangle.

A series of pair-wise t-tests were conducted on the search slope data, derived by linear regressions of the RT means against set size for each participant. For target present situations, the slopes were significantly different between the *both* and the *subjective* condition, $t=-4.1$, $p<0.01$; and between the *line* and the "subjective condition, $t=-2.5, p<0.05$. The slopes were marginally significant different between the *both* and the *line* conditions, $t=-2.1$, $p=0.056$. For the target absent condition, the slopes were significantly different between the *both* condition and the *subjective* condition, the *line* condition and the *subjective* condition, $t=-8.2$ and -6.9 respectively, $ps<0.05$. The slope was marginally different between the *both* condition and the *line* condition, $t = 1.86$, $p=0.08$.

Discussion

Although the stimuli were limited to a region which encompassed only 4.5° by 4.5° visual angle, we found the same pattern of results as Experiment 1. The search was much more efficient in *both* and *line* conditions than in the *subjective* condition.

Compared with the results of Experiment 1, the slope was smaller in thc *both* condition and the *line* condition, while the slope was larger in the *subjective* condition. This showed that serial search in the *subjective* condition in Experiment 1 is not due to eccentricity.

The pattern of reaction time in the *line* condition was strange. The reaction was faster for the target absent condition than the target present condition. We don't have an explanation for this pattern, but it does not affect the conclusion about the inefficiency of subjective figure search.

Experiment 5

A rclatively weak targct stimulus can be hard to find among concurrent nontarget stimuli that induce a more powerful neural response (Treisman & Gormican, 1988). A possible reason for the results of the first two experiments has to do with the stimuli used. All of the above experiments utilized Kaniza-type figures with high-contrast pacmen as inducing stimuli. If subjective contours are treated as low-contrast luminance edges by the visual system, then it is reasonable to expect that the high-contrast edges elsewhere in the display will impair detection of the subjective contours. Just as attention may be needed to gain access to the presence of a low-contrast luminance contour in the context of many high-contrast luminance contours, attention may be needed to detect a subjcctivc contour among many high-contrast

luminance contours. Subjective contours may be perceived preattentively, and attention may then act only to improve the signal-to-noise ratio.

Experiment 5 was designed to exclude the possibility that Kaniza figures cannot be found efficiently because the inducers were so vivid that they somehow hide the subjective contour. If the explanation above is correct, then the slope should vary significantly with real contours if the contrast of the contours is varied across trials. A real contour that is very faint should produce a search that is as inefficient as that in the *subjective* condition of Experiment 1.

Stimuli and procedure

17 participants participated in this experiment. Each participant performed five blocks of trials. Each block had one stimuli type. One block had *subjective* figures. The other four were were the *both* condition with the contours in each block having a different gray level. The *both* condition with different gray level were called *both0, both1, both2, both3,* whose gray level were 6, 16, 39, and 60 cd/m^2 in sequence. The gray level of the real contour in the "both1" condition was similar to that of the real contour used in the first four experiments. The set sizes were 5, 7, 9, and 13. In half of trials, target was present. With the variations in set size, stimulus type, and target presence, there were 40 conditions in this experiment, with 8 trials for each condition. Thus, there were a total of 400 experiment trials for each participant. At the beginning of each block, there were 32 practice trails. All of the other aspects of this experiment were exactly similar to experiment 1.

Results

The overall accuracy was 96.1%. Because the accuracy was very high, it was not further analyzed. Only trials with correct responses were included in the analysis, which excluded 268 trials among 6800 trials. Trials with reaction times shorter than

100 ms or longer than 10000ms were also excluded, which resulted in an additional 11 trials being excluded. Overall 4.1% of all of the trials were excluded from analysis.

For the *both* conditions, the slopes of reaction time as a function of set size, for the *both0, both1, both2, both3* condition in sequence, were 14.26, 9.96, 12.89, and 15.56 ms/item respectively for the four gray levels when the target was present, and 34.36, 26.40, 35.84, and 49.32 ms/item when the target was absent. In contrast, in the *subjective* condition, the target-present slope was 34.74 ms/item, and the target-absent slope was 81.80 ms/item.

A series of pair-wise t-tests was conducted on the search slope data, derived by linear regressions of the mean RTs against set size for each participant. For target present conditions, the slopes were significantly different between the *both* condition in all of four gray levels and the *subjective* condition, t = -3.5, -3.7, -2.9, -3.5 respectively, ps <0.05. When the target was absent, the slopes were significantly different between the *both* condition in all of four gray levels and the *subjective* condition, t = -5.9, -6.3, -4.9, -3.9 respectively, ps <0.05. When conducting all of the possible paired-samples t-test comparing different levels of the *both* condition, no pair reached significance, ps>0.10 when the target was present or when the target was absent.

Discussion

In this experiment, search performance between the *both* conditions in all of the four gray levels of real contour were not significantly different from one another. In contrast, the performances of all four *both* conditions with different gray levels, even the most faint one, were significantly different from the *subjective* condition. From this result, we can see that the inefficiency in the *subjective* condition can not be explained by the faintness of the subjective contours.

Discussion of Experiments 1-5

The major idea behind these experiments is the comparison of search performance of the *both* condition and the *subjective* condition. Because the only difference between these two conditions is whether real contours are present or not in the stimuli, any difference in search performance must be attributed to the perception of subjective contour. Results in Experiment 1 and Experiment 2 show that the search is inefficient in the *subjective* condition. However it is much more efficient in the *both* condition compared to the *subjective* condition. The different performance between these two conditions indicate that the perception of subjective contour requires attention. Experiment 1 used orientation to distinguish target and distracters, while Experiment 2 used shape. Though they used different stimuli, same pattern emerged, demonstrating the robustness of the result.

Stimuli were carefully designed to reduce the information that may distinguish target and distracter other than orientation of shape. In Experiments 1 and 2, the pacmen were identical for both target and distracters, so participants could not use information other than subjective figure to find the target.

Visual acuity falls sharply as distance from the fovea increases. At a distance of 1°, visual acuity has fallen off by a factor of two or three, and the intercone spacing and the density of ganglion cells show corresponding changes (Carpenter, 1988, p6). Experiments 3 and 4 exclude the possibility that visual acuity is the major factor that influences the results of Experiment 1 and 2. Experiment 3 shows that even at large retinal eccentricity condition, the accuracy of perception of the inducers is quite high. In Experiment 4, in which the region occupied by the stimulus display was smaller,

the result was similar to Experiments 1 and 2. It shows that retinal eccentricity can not explain the results we got in Experiments 1 and 2.

Experiment 5 shows that performance did not differ significantly with different gray levels. And even the faintest condition produces significantly more efficient search than the *subjective* condition. This result strongly argue against an explanation based on weak subjective contours being obscured by stronger real contours.

Our result is consistent with Grabowecky and Tresiman's (1989), but it is inconsistent with Davis and Driver (1994). As explained in the introduction, their result may be due to factors other than the perception of subjective contour. Our result is also different from that of Davis and Driver (1998). As we have reviewed in the introduction section, Davis and Driver's (1998) paradigm was quite indirect. They used three pacmen to induce a subjective figure, and they used a questionable assumption that subjective figure can act as occluding surfaces. We use an different approach, and have gotten apparently different result as theirs. We believe that the paradigm of our experiment is more straightforward comparing with theirs.

CHAPTER 3

SUBJECTIVE FIGURES INDUCED BY LINE ENDS

All of the experiments described so far explored Kanizsa type subjective figures. As we have reviewed in the introduction, the perception of subjective figures induced by line ends may be different from that of Kanizsa type subjective figures. Though Experiments 1 to 5 have shown that the perception of Kanizsa type subjective figures requires attention, the perception of subjective figures induced by line ends may be different. Experiment 6 and 7 uses a similar paradigm to explore what will happen in subjective figures induced by line ends.

Experiment 6

Stimulis and procedure

The stimuli are shown in Figure 14. The subjective figures were induced by interlaced black and white line segments on gray background (16 cd/m^2). The target and distracters were all rectangles, whose ratio of length and width was 3:1. In the "subjective" condition, the stimuli were induced by line ends only. In the *both* condition, at the exact position of subjective contour, there were real contours of one of the three gray levels, which were 6, 39, and 60 cd/m^2 for the *both0, both1, both2* condition in sequence. The task was to search for a target which was a rectangle slanting right. The target was present on half the trials. The set size was 5, 7, 9, or 13. 12 subjects participated in this experiment. At the beginning of each trial, a red cross appeared at the center of the screen for 1 second. Then the search array then appeared and was present until response.

Results

The accuracy was 97.8%. Because accuracy was very high, it was not analysised further. Trials with incorrect responses were excluded from analysis, which excluded 85 trials among 3840 trials.

In the *both* condition, the slope of the mean reaction time as a function of set size was -1.08,-3.29,-3.03 ms/item for gray level 1 to level 3 respectively when the target was present, and 7.40, 12.77, 14.94 ms/item when the target was absent (Figure 15). In the *subjective* condition, the target-present slope was 2.00 ms/item, and the target-absent slope was 13.72 ms/item.

A series of pari-wise t-tests was conducted on the search slope data, derived by linear regressions of the mean RTs against set size for each participant. The comparison of the mean RTs between all of the possible pairs of conditions was conducted. None of these t-tests reached significance, ps>0.1.

Discussion

Results showed that search in both the *subjective* condition and the *both* condition were efficient, and that there were no difference in the performance between the four conditions.

Experiment 7

In Experiment 6, we used rectangles whose ratio between length and width was 3:1. The rectangles were either tilted 45 degree left or 45 degree right from vertical direction. These rectangles were different from those in Experiment 1. To allow comparison across experiments, we controlled these factors in Experiment 7.

Stimuli and procedure

In this experiment, the task was to search for a horizontal rectangle among vertical rectangles. The ratio of the length and width of the rectangle was 1.5:1, which was similar to that used in Experiment 1. The stimuli are shown in Figure 16. There were two conditions in this experiment. The first one was the *subjective* condition, with subjective figures induced by line ends. The second one was the *both* condition, in which the rectangles were defined by both real contours and subjective contours. In the *both* condition, the real contour was one of two gray levels. Gray level in the *both0* condition was lighter than the background ($60\,cd/m^2$), while gray level in the *both1* condition was darker than the background ($6\ cd/m^2$). All of the other aspects of the stimuli were similar to those of Experiment 1. The procedure was similar to experiment 6. 18 new participants who had never participated in any of the previous experiments participated in this experiment.

Results

The overall accuracy of this experiment was 95.9%. Only trials with correct responses were included in the analysis, which excluded 177 trials among 4320 trials. Trials with reaction times shorter than 100 ms or longer than 10000ms were also excluded from analysis, which excluded an additional 9 trials.

The results are shown in figure 17. In the *both* condition with a contour of gray level 1, the mean slope for reaction time as a function of set size was 13.2 ms/rectangle when the target was present, and 38.81 ms/rectangle when the target was absent. In the *both* condition with a contour of gray level 2, the mean slope of reaction time as a function of set size was 14.2 ms/rectangle when the target was present, and 34.36 ms/rectangle when the target was absent. In the *subjective*

condition, the target-present slope was 13.0 ms/rectangle when target present, and the target-absent was 46.10 ms/rectangle.

A series of pair-wise t-tests was conducted on the search slope data, derived by linear regressions of the RT means against set size for each participant. In both the target present condition and target absent condition, all of the possible pair-wise t-tests were not significant ($p>0.05$).

Discussion

In experiment 7, search performance was more inefficient than in Experiment 6, indicating that the task in Experiment 7 is much harder than that of Experiment 6. What is most interesting to us is that there was no difference in the performance of search in all of the three conditions.

Discussion of Experiments 6-7

Visual search in both Experiments 6 and 7 are efficient. However, there are factors to consider that might explain why the perception of subjective contour induced by line ends is efficient, as highlighted by Davis and Driver's (1998) argument against Gurnsey et al.'s (1992) result. They argued that the efficient search in Gurnsey et al. (1992) was caused by blurring in peripheral vision. Visual spatial information is filtered by spatial frequency-orientation channels in the visual system (Sekuler, 1974; Hubel & Wiesel, 1974). Instead of using subjective contour information in visual search, subjects may use low spatial frequency information in their search for the target (Ginsberg, 1975). By removing high spatial frequency components in an image, and leaving only the low spatial frequency components we simulate the information that is available to neurons with large receptive fields that only respond to low spatial frequencies. Figure 17 presents a version of the stimuli

from experiment 6 that is blurred by filtering out the high spatial frequency components. It seems that in this image the texture is enough to distinguish target and distractors.

Based on these data, we are not ready to conclude that perception of subjective figures introduced by line end does not require attention. More work is needed to explore this problem. Based on Experiments 1-5, we do conclude that perception of Kanizsa type of subjective figures requires attention, but we cannot extend this conclusion to other types of subjective figures. The neural evidence mentioned in the introduction also suggests differences in how these different types of subjective contour are perceived.

CHAPTER 4

GENERAL DISCUSSION

Using the visual search paradigm, this paper proposed a new approach to settle the problem of whether perception of subjective contour requires attention or not. Instead of only looking at the slope of reaction time, we compared the search performance of the condition of interest (sometimes the *line* condition, and sometimes the *subjective* condition) with control condition (the *both* condition). Because the test condition differed from the control condition only in one factor, the difference in search performance must due to that different factor. Our experiments showed that visual search for Kanizsa subjective figures is inefficient, while search in the figures induced by a combinatinon of real lines and pacmen was much more efficient. Because the only difference between the *both* condition and the *subjective* condition was whether a real contour present or not, the search performance difference must be due to the perception of the subjective figure. This result suggests that visual attention is required in the perception of Kanizsa-type subjective contours.

Another interesting finding comes from the comparation between the *line* condition and the *both* condition. In Experiments 1, 2, 4 and 5, the slope of reaction time as a function of set size was not significantly different between these two conditions. The difference between the stimuli of these two conditions was whether pacmen were present or not. This result showed that the black pacmen did not efficiently inhibit the percept of real contours. Results of Experiment 5 provided stronger evidence about this finding.

The same kind of experimental test showed that visual search of subjective figures induced by line ends was efficient in the *subjective* condition. Both the

reaction times and the slopes of reaction time were not significantly different between any pair of the conditions tested. However, as we have shown in Chapter 3, the efficient search with subjective figures induced by line ends may be due to salient features other than subjective contour. We cannot be certain that the perception of subjective contour induced by line end does not require attention. Though we can not reach a conclusion on whether the perception of subjective contour requires attention or not, we can be more confident that Kaniza type subjective figure requires attention. As explained in the introduction, the mechanism of the perception of Kanizsa type subjective figures may be different from that of subjective figure induced by line end.

It has been widely argued that the study of such subjective figures may allow a privileged view of the mechanisms involved in the perception of contours, brightness, shapes, and surfaces (Petry & Meyer, 1987). Distinguishing whether the perception of subjective contour requires attention or not may help to understand the mechanism of subjective contour perception. Contrary to some authors' argument, this paper provides strong evidence supporting the idea that perception of subjective contour requires attention. So any theory that tries to explain subjective contour perception without attention can not be correct.

Just as these results contribute to the understanding of subjective contour, they also contribute to the understanding of attention. Many attention theories assume that attention is guided by preattentive features (Cave & Wolfe,1990; Treisman & Gelade, 1980; Wolfe, Cave & Franzel, 1989). These theories cannot be fully described and tested without an explicit specification of which types of processing are done without attention, and which types of processing require attention (Wolfe, 1998). From this series of experiments, it is quite clear that subjective contour should not be considered as a preattentive feature that may guide attention deployment. This knowledge allows

us to understand the capabilities of preattentive mechanisms in vision, and also to understand why attention is necessary.

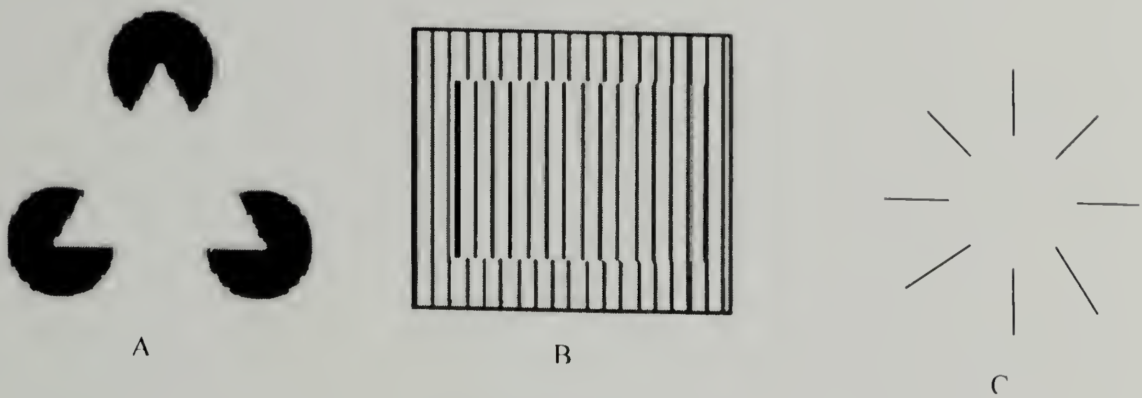


Figure 1. Examples of subjective figures. A: Kanizsa type subjective figure. B: Subjective contour induced by line-end. (Figures are adapted from Davis & Driver ,1998)

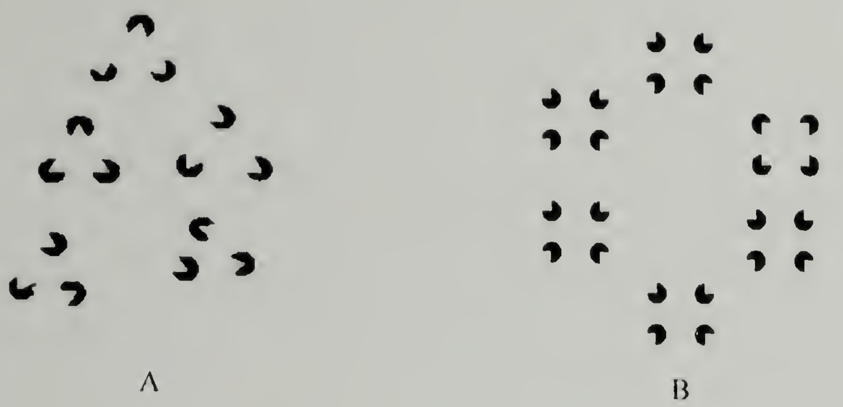


Figure 2. Experiments using visual search paradigm. (A) Stimuli used in Grabowecky & Treisman (1989) (B) Stimuli used in Davis & Driver (1994) (Figures are adapted from Grabowecky & Treisman, 1989 and Davis & Driver ,1994).

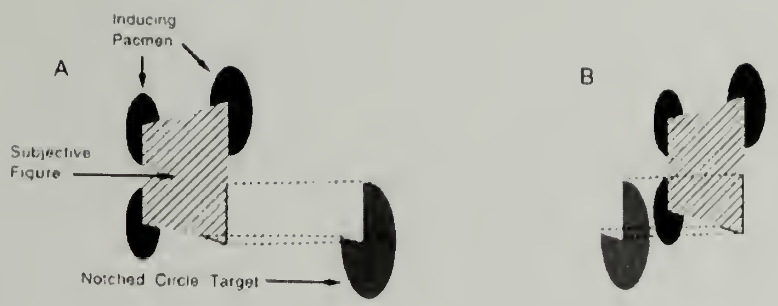


Figure 3. A: Schematic depiction of the arrangement in depth for a target cluster in Davis & Driver (1998). The large brown notched target lies in the back plane, as indicated by the dotted lines, with three black pacmen in front. (Figures are adapted from Davis & Driver ,1998).

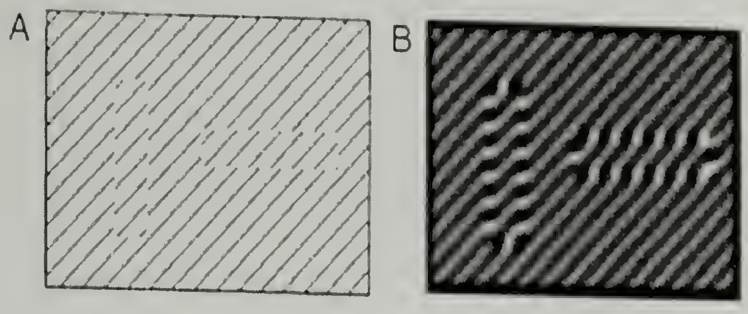
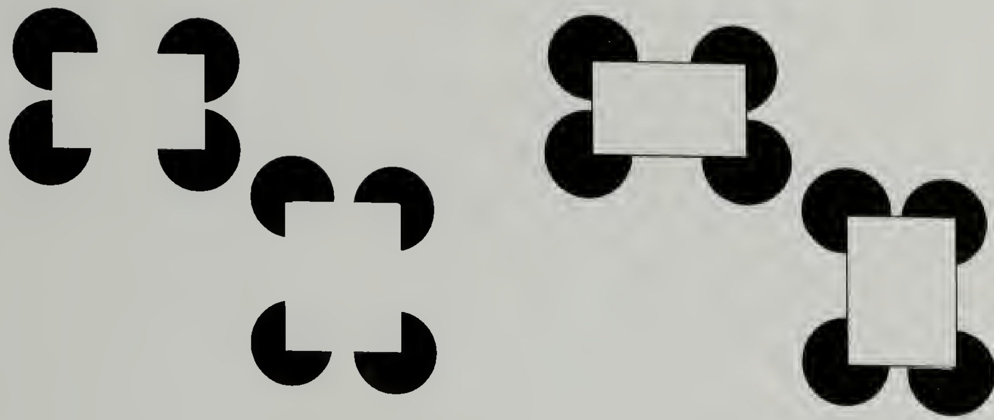


Figure 4 Example target and nontarget stimuli from the visual search study of Gurnsey et al. (1992). A: Vertical and horizontal bars defined by offset tilted gratings. B: Low-spatial-frequency version of the image in A.



A. B.

Figure 5 Compare of subjective condition and both condition. A. subjective condition, B. both condition

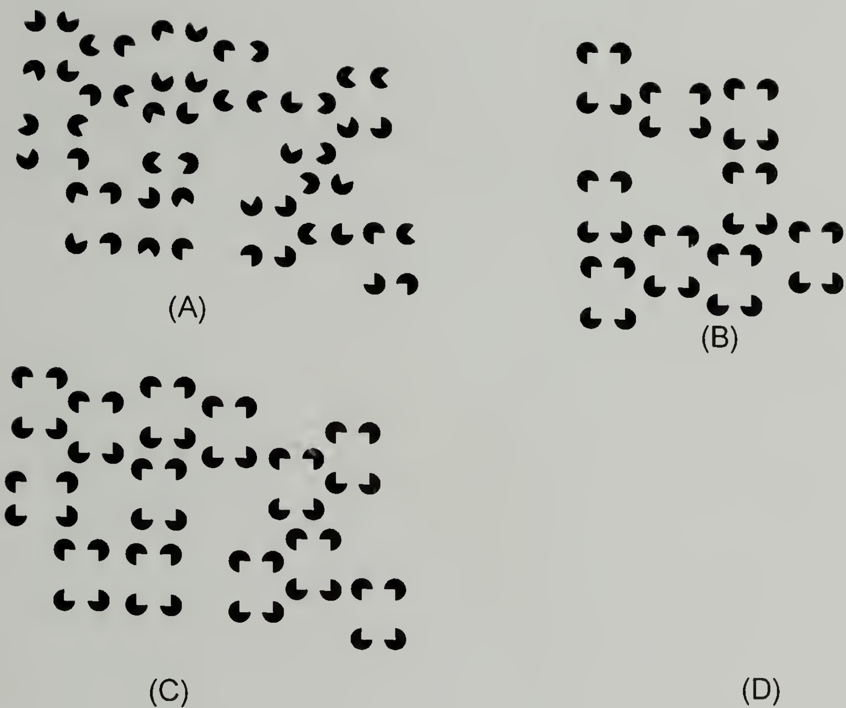


Figure 6 Stimuli of Experiment 1. (A) Place holder for the stimulus shown in C. (B) Simulus from both condition (C) Stimulus from subjective condition (D) Stimulus from line condition

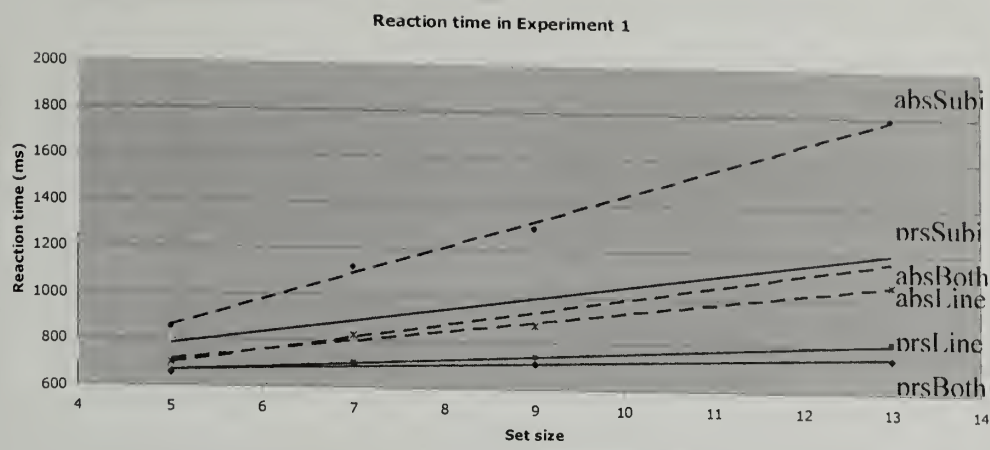


Figure 7 Reaction time as a functions of set size for each condition of Experiment 1.

Figure 8 Stimuli of Experiment 2. Only both condition is shown.

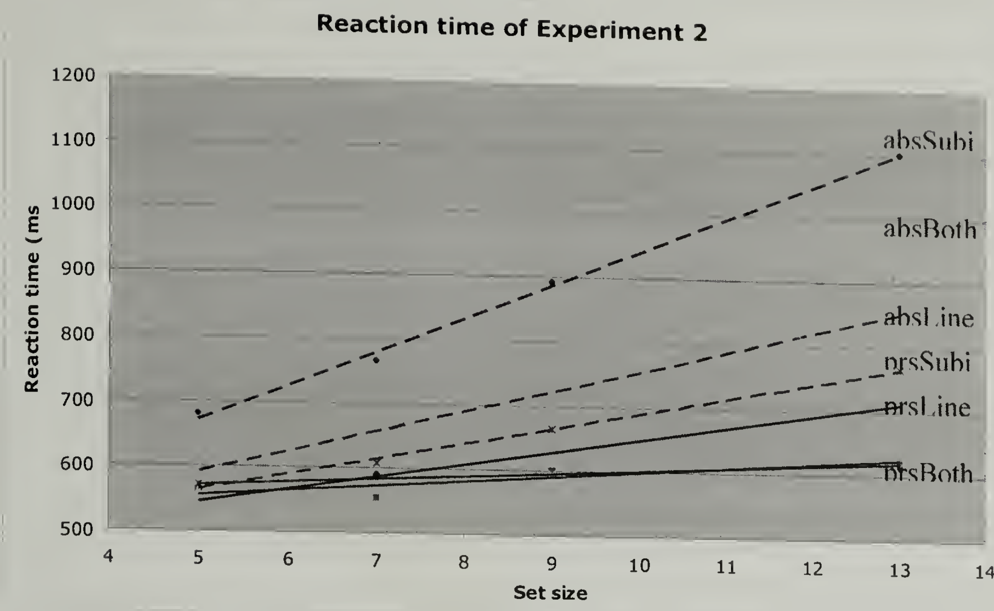


Figure 9 Reaction times from Experiment 2.

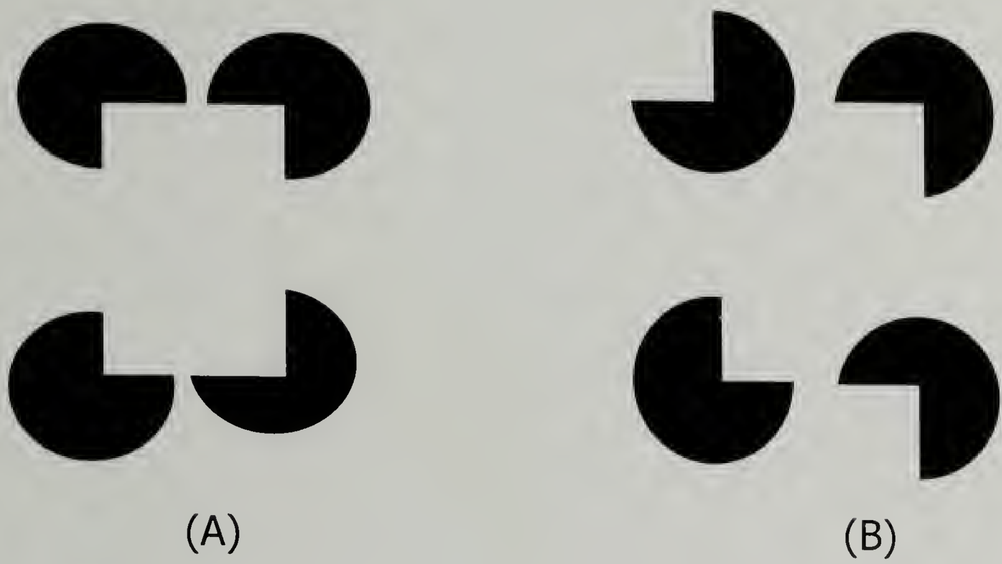


Figure 10 Stimuli of Experiment 3. A. Subjective figure. B. Non subjective figure.

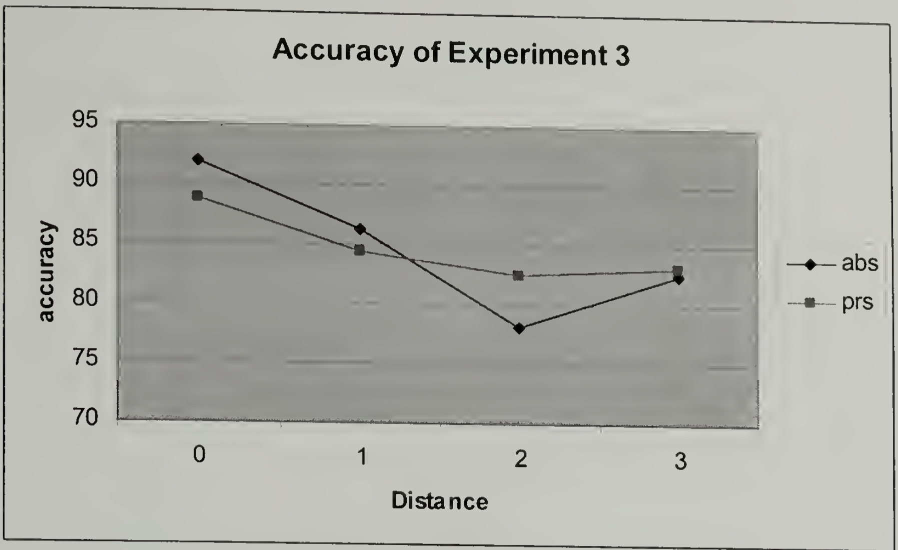


Figure 11 Accuracy of Experiment 3.

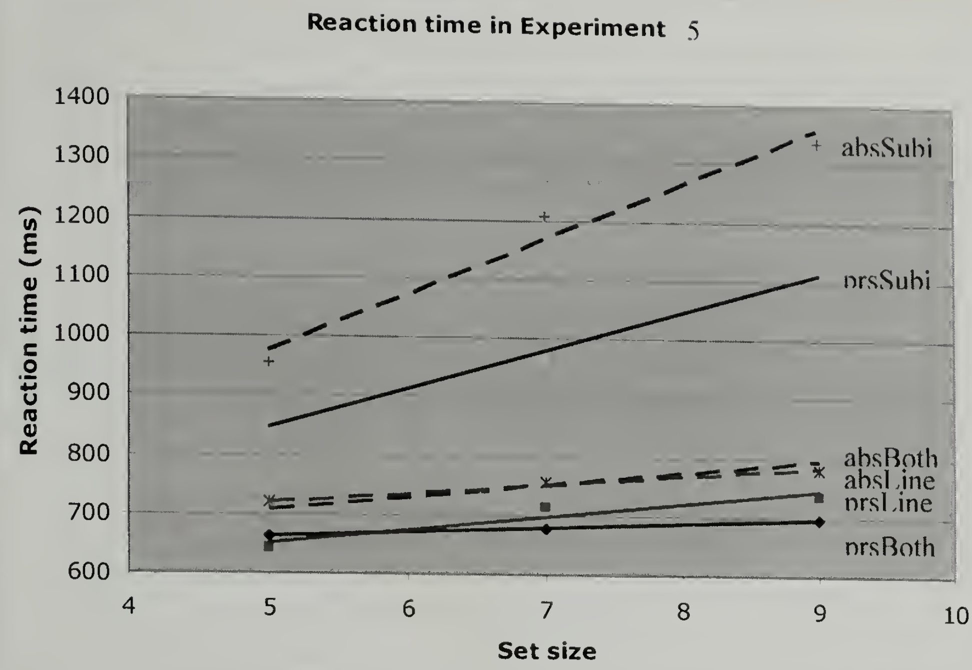


Figure 12 Reaction time of Experiment 5.

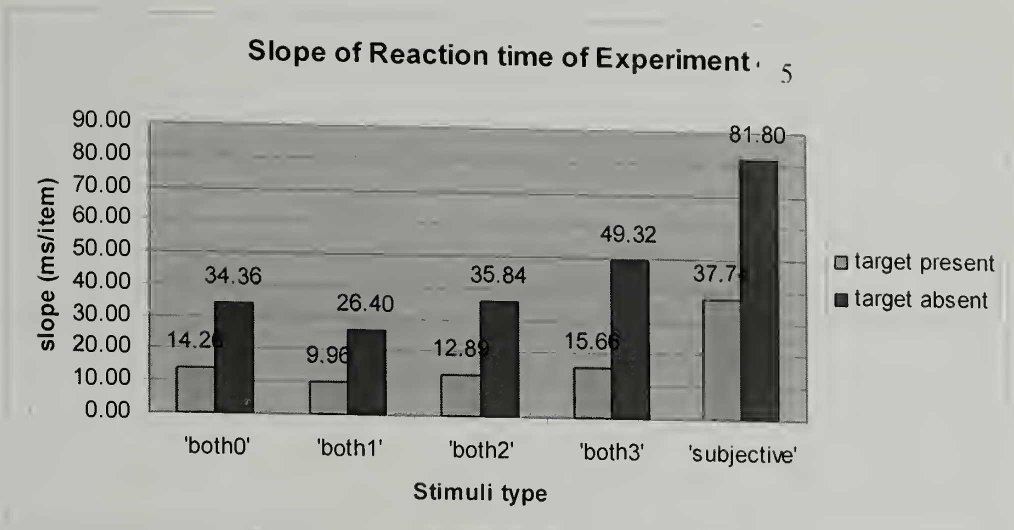


Figure 13 Slope of reaction time of Experiment 5.

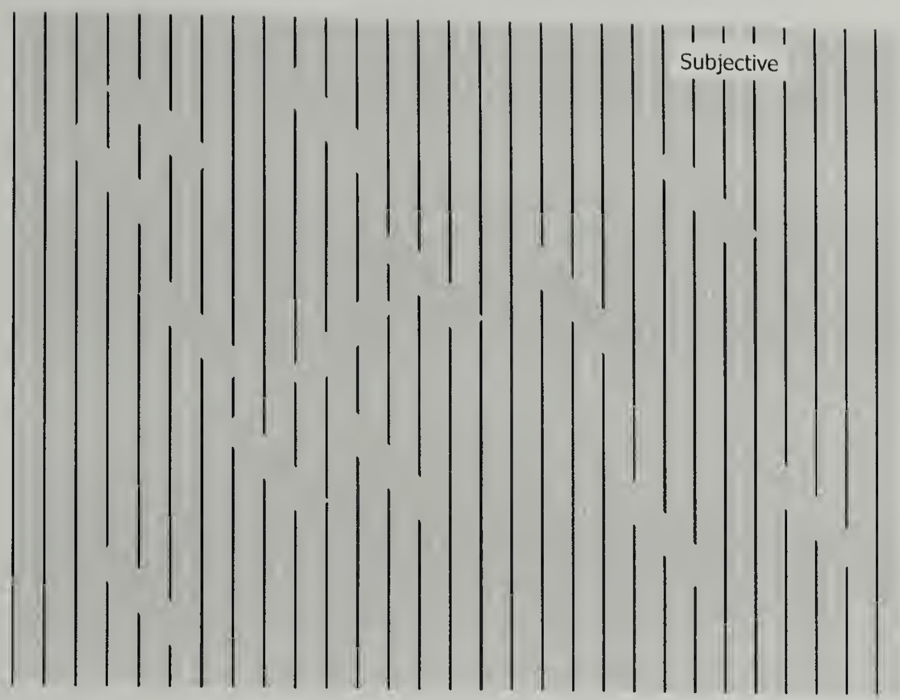


Figure 14 Stimuli of Experiment 6.

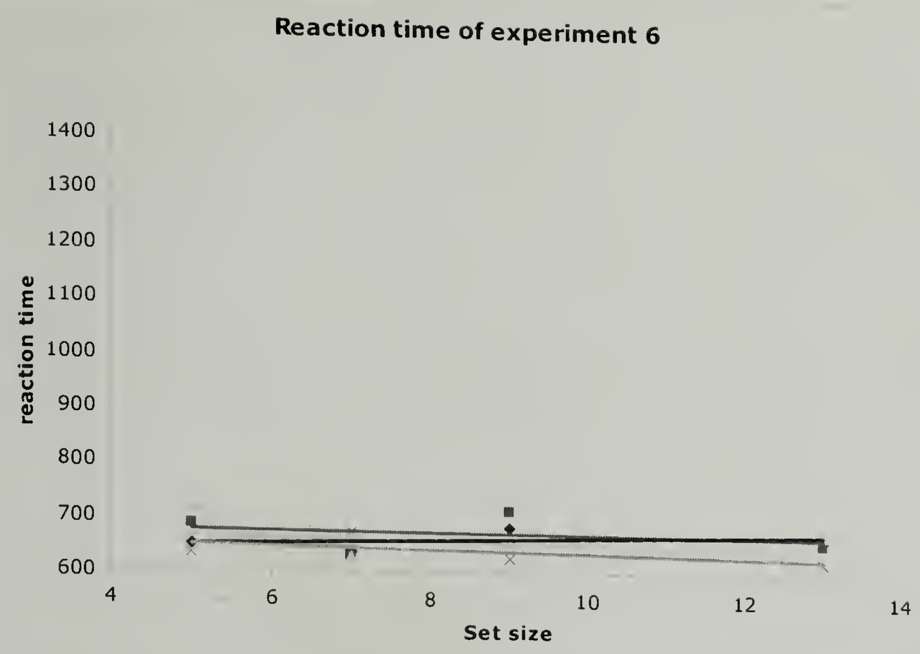


Figure 15. Reaction time of Experiment 6. Only target present conditions are shown.

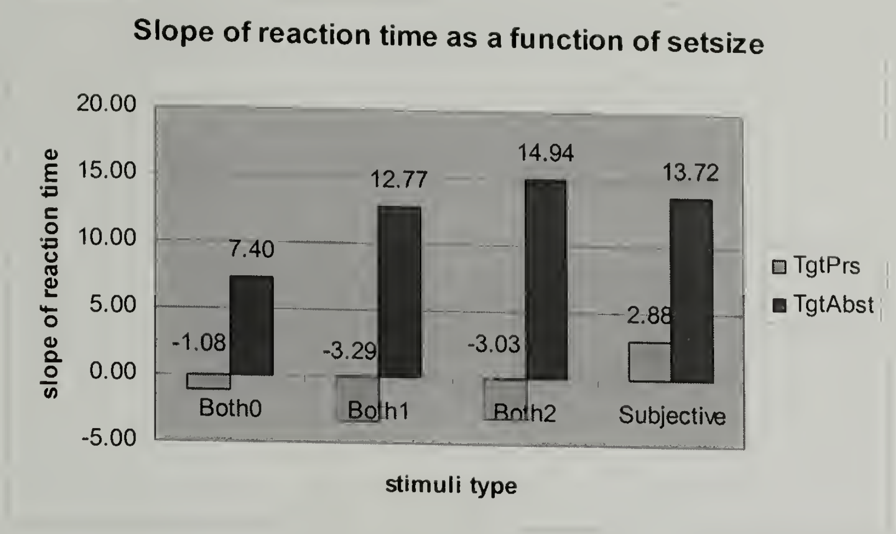


Figure 16 Slope of reaction time of Experiment 6

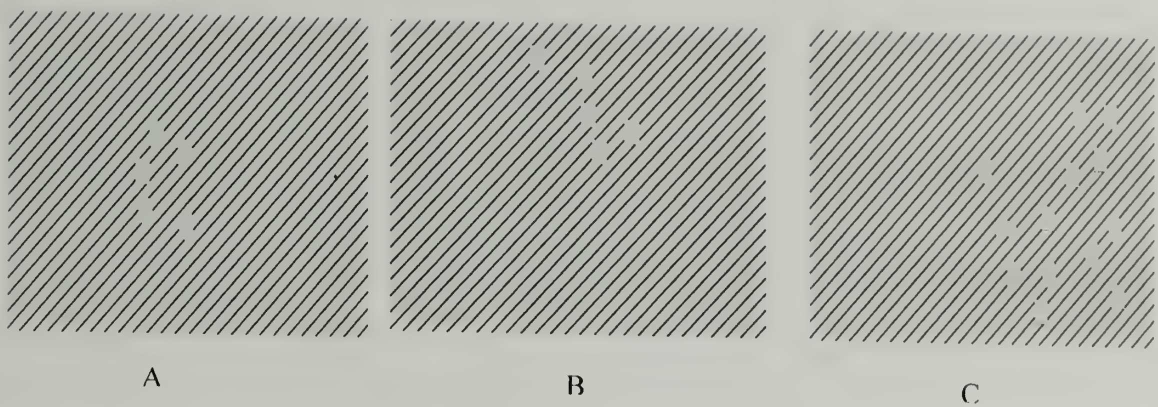


Figure 17 Stimuli of Experiment 7. A: Subjective condition. B. "both 1" condition, the real contour is lighter than background. C. "both 2" condition, real contour is darker than background.

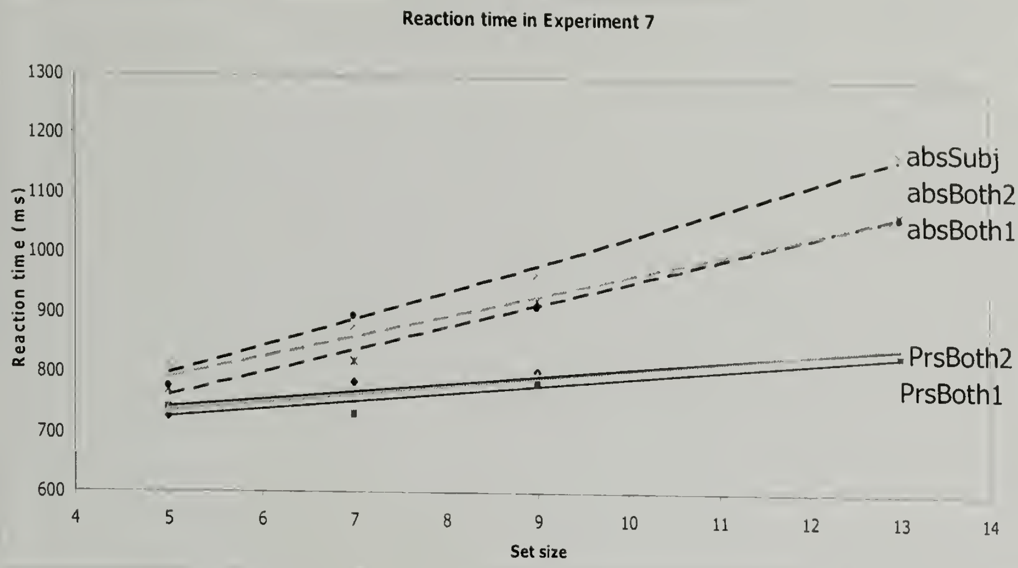


Figure 18. Reaction time Experiment 7.

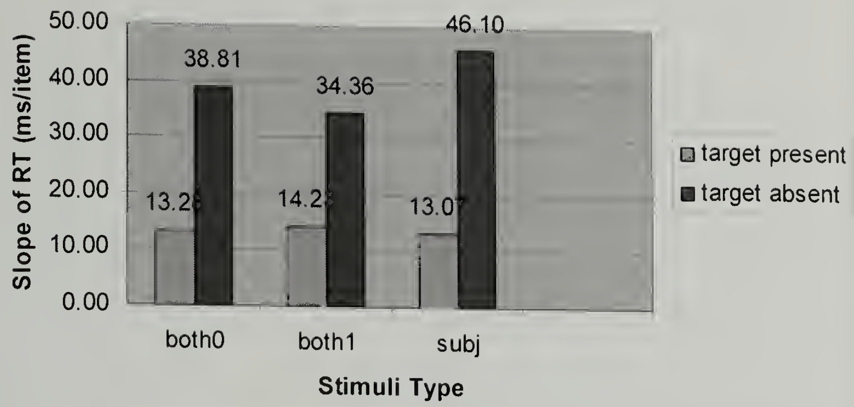


Figure 19 Slope of reaction time of Experiment 7.

Figure 20 Filtered result of stimuli of Experiment 6.

Cave, K. R. and Wolfe J.M. (1990). Modeling the Role of Parallel Processing in Visual-Search. *Cognitive Psychology* 22, 225-271.

Davis G., & Driver J. (1994). Parallel detection of Kanizsa subjective figures in the human visual system. *Nature*, 371, 791-793.

Davis, G. & Driver, J. (1998). Kanizsa subjective figures can act as occluding surfaces at parallel stages of visual search, *Journal of Experimental Psychology:Human Perception and Performance*, 24, 169-184.

Driver, J., Davis, G., Russell, C., Turatto, M., & Freeman, E. (2001). Segmentation, attention and phenomenal visual objects. *Cognition*. 80(1,2), 61-95.

Fahle, M., & Koch, C. (1995). Spatial displacement but not temporal asynchrony destroys temporal binding. *Vision Research*, 35, 491-494.

Ginsberg, A. P. (1975). Is the illusory triangle real or imaginary? *Nature*, 257, 215-220.

Grabowecky, M., & Treisman, A. (1989). Attention and fixation in subjective contour perception. *Investigative Ophthalmology and Visual Science, Supplement*, 30, 457.

Grosof D.H., Shapely, R.M., & Hawken, M.J. (1993). Maccaque V1 neurons can signal “illusory” contours. *Nature*, 365, 550-552.

Gurney, R., Humphrey, G.K., & Kapitan, P. (1992). Parallel discrimination of subjective contours defined by offset gratings. *Perception & Psychophysics*, 52, 263-276.

Gurnsey, R., Poirier F., & Gascon, E. (1996). There is no evidence that Kanizsa-type subjective contours can be detected in parallel. *Perception*, 25, 861-874.

Heydt, R. von der., Peterhans, E., & Baumgartner, G., (1984). Illusory contours and cortical neuron responses. *Science*, 224, 1260-1262.

Heydt, R. von der., & Peterhans, E. (1989). Mechanisms of contour perception in monkey visual cortex, Lines of pattern discontinuity. *Journal of Neuroscience*, 9, 1731-1748.

Hubel, D. H. and Wiesel T.N. (1974). Sequence regularity and geometry of orientation columns in monkey striate cortex. *Journal of Comparative Neurology*. 158, 267-294.

Kanizsa, G., (1979). Organization in vision. New York: Praeger.

Lesher, G. W. (1995). Illusory contours: Towards a neurally based perceptual theory. *Psychonomic bulletin & Review*, 2, 279-321.

Mattingley, J, Davis, G., & Driver, J. (1997). Preattentive filling-in of visual surfaces in parietal extinction. *Science,* 275, 671-674.

Meyer, G. E., & Fish, D. (1987). Illusory contours, texture segregation and a configural inferiority effect. In Petry, S., Meyer, G. E. (Eds), The *perception of Illusory Contours* (pp.224-234). New York: Springer.

Meyer, G. E., & Petry, S. (1987). Top-down and bottom-up: the illusory contour as a microcosm of issues in perception. In Petry, S., Meyer, G. E. (Eds), The *perception of Illusory Contours* (pp.3-19). New York: Springer.

Petry, S. & Meyer, G. E. (1987). *The perception of illusory contours.* New York/Berlin: Springer-Verlag.

Pritchard, W.S., & Warm, J.S. (1983). Attentional processing and the subjective contour illusion. *Joruna1 of Experimental Psychology: General*, 112, 145-175.

Ringach, D. L. & Shapely, R. (1996). Spatial and temporal properties of illusory contours and amodal boundary completion. *Visual Research*, 36, 3037-3050.

Rock, I. & Anson, R. (1979). Illusory contours as the solution to a problem. *Perception,* 8, 665-681.

Sekuler, R. (1974). Spatial vision. *Annual Review of Psychology*, 25, 195-232.

Shapley, R., & Gordon, J. (1985). Nonlinearity in the perception of form. *Perception & Psychophysics*, 37, 84-88.

Townsend J.T. (1990). Serial vs Parallel processing – sometimes they look like tweedledum and tweedledee but they can (and should) be distinguished. *Psychological Science,* 1, 46-54

Treisman, A., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, 12, 97-136.

Vuilleumier, P, Valenza, N., & Landis, T. (2001). Explicit and implicit perception of illusory contours in unilateral spatial neglect: behavioural and anatomical correlates of preattentive grouping mechanisms. *Neuropsycholgia*, 39, 597-610.

Wolfe, J. M., Cave K.R. & Franzel S.L. (1989). Guided Search - an Alternative to the Feature Integration Model for Visual-Search. *Journal of Experimental Psychology-Human Perception and Performance* 15, 419-433.

Wolfe, J.M. (1998), Visual attention, in Pashler H., editor. *Attention*. London UK: University College London Press.